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MATERIAL INTERACTIONS WITH THE LOW EARTH ORBITAL ENVIRONMENT: ACCURATE REACTION RATE MEASUREMENTS

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Abstract

An understanding of the surface chemistry which gives rise to atom/surface interactions within the orbital environment is crucial to establishing a reliable materials interaction data base for Space Station and verifying the operational capability of ground-based neutral beam facilities which simulate the space environment. One of the more important effects of these interactions is oxidation of material surfaces by atomic oxygen, a major constituent of the low Earth orbital environment. Material interaction studies conducted during flights STS-5 and STS-8 have provided most of the current information regarding the reactivity of spacecraft materials to atomic oxygen, and the results of these studies indicate many materials such as organic films, polymers and many composites, react readily with atomic oxygen and have reactivities in the range 2.5×10^{-24} to 3.0×10^{-24} cubic centimeters per atom.

The data base provided by these flight programs is limited in its application, however, because no information is currently available which adequately explains the basic mechanisms responsible for atom/surface interactions. Another more serious limitation to this data base is the total integrated atomic oxygen flux (fluence) derived for these flights and used to determine material interaction rates that have been estimated using thermospheric models to predict atomic oxygen number densities within the orbital environment. Typically, errors of $\pm 25\%$ or greater can be expected for these density estimations, and since they were used to compute fluence, these errors also appear in the surface recession rates for Space Station materials.

To resolve these uncertainties and provide reaction product compositional data for comparison to data obtained in ground-based laboratories, a flight experiment has been proposed for the Space Shuttle which utilizes an ion-neutral mass spectrometer to obtain in-situ ambient density measurements and identify reaction products from modeled polymers exposed to the atomic oxygen environment. An overview of this experiment will be presented and the methodology of calibrating the flight mass spectrometer in a neutral beam facility prior to its use on the Space Shuttle will be established.

Introduction

A reliable materials interaction data base and an understanding of the surface chemistry which gives rise to the interaction of surfaces with atomic oxygen, the principal constituent within the low Earth orbital (LEO) environment, are crucial to the development of materials and coatings for future spacecraft, such as Space Station, designed to operate for extended

(10 to 30 yr) periods at low (300 to 500 km) orbital altitudes. Previous Space Shuttle flights[1,2,3] have shown that many polymers, organic films, and composite materials used in typical spacecraft applications undergo significant mass loss when exposed at low altitudes to the orbital environment. Polyimide films used as substrates for lightweight, large-area solar arrays, such as those proposed for Space Station, had relatively high rates of surface recession when exposed to atomic oxygen. Polyurethane paints used to suppress stray light within astronomical telescopes and in thermal control coatings for spacecraft structures were found to degrade,[4] with specular paints becoming more diffuse and thermal control paints acquiring a chalky, particulate residue on their surfaces. Metals such as carbon, osmium, and silver were also reactive in the flight environment[5] and underwent significant mass loss, in the case of osmium and carbon, and gross oxidation, in the case of silver. Graphite epoxy composites proposed for lightweight truss members in large space structures lost significant mass[6] when exposed to moderate atomic oxygen fluxes (10^{14} to 10^{15} atoms/cm^2-sec) for limited periods.

An interaction data base has been developed for these and other materials to aid in spacecraft design. The data base provided by previous Space Shuttle flights is limited in its application, however, because total integrated atomic oxygen flux (fluence) used to derive material reaction rates must be estimated using thermospheric models[7] to predict atomic oxygen number densities. Typically, errors of $\pm$25% or greater can be expected for these density estimations, and, since they are used to compute both fluence and reactivity, these errors also appear in the data base. Another limitation is the lack of available information which adequately explains the details of the interaction process and the chemical mechanisms responsible for surface recession. These mechanisms must be understood to enable selection of coatings or new materials that do not readily degrade in the LEO environment.

Proposed Flight Experiment

To resolve many of these uncertainties and provide a more accurate data base, a materials interaction flight experiment designated EOIM-3 (Evaluation of Oxygen Interactions with Materials, third series) has been proposed. The EOIM-3 experiment uses an ion-neutral mass spectrometer and a carousel system (Fig. 1) to conduct aeronomy measurements and to study surface interaction mechanisms. In addition to obtaining accurate reaction rate measurements for materials, this experiment will use the mass spectrometer to measure the local Space Shuttle environment over many orbital passes to develop a more thorough understanding of the ionospheric processes and to obtain correlations of orbital ion/neutral number densities with ambient density models.

To implement these objectives, the mass spectrometer (Fig. 2) will be positioned within the Orbiter bay on a rotatable mount (Fig. 3) to view first along the Orbiter +Z-axis (aeronomy measurements) and then toward materials installed on a rotatable carousel. The carousel will have five sectors, each containing materials with different chemical compositions, which will be rotated sequentially to face the mass spectrometer. Where possible, these materials will be isotopically labeled with carbon-13 and

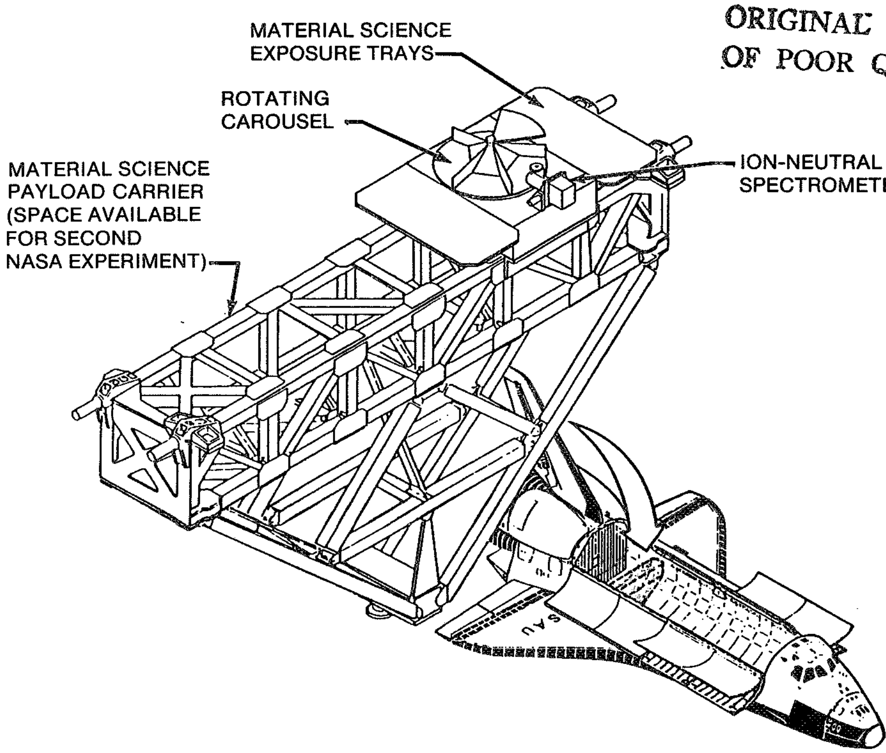

Fig. 1 EOIM-3 atomic oxygen effects experiment.

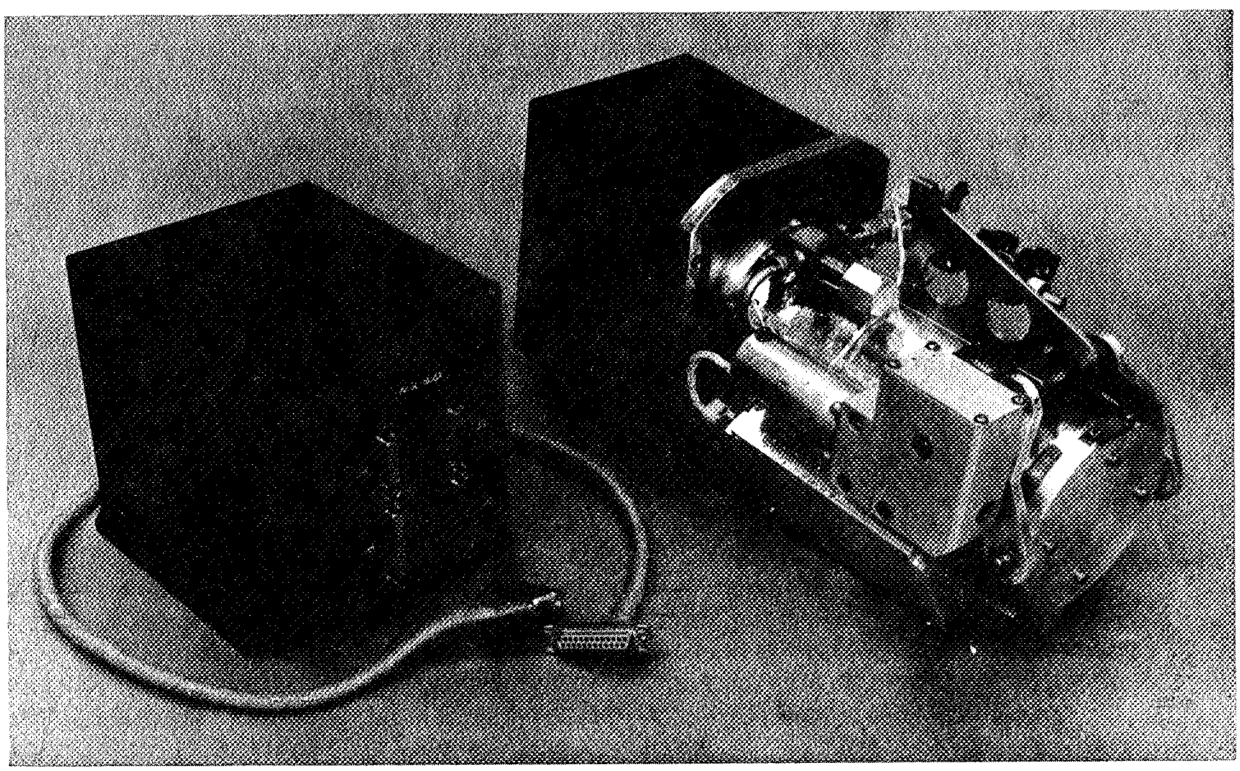

Fig. 2 Ion-neutral mass spectrometer. The control unit to the left of the sensor is preprogrammed prior to flight.

deuterium to differentiate the reaction products from the overall instrument background. Measurements of gases produced by the interaction of atomic oxygen with the carousel materials will aid in identifying chemical mechanisms which give rise to surface recession. Materials proposed for mechanistic studies include polyimide, carbon, polyvinylchloride, polystyrene, labeled polyethylene, polyurethane light-absorbing paint or similar material, and gold or aluminum oxide as a control surface.

Reaction Rate Measurements

Accurate reaction rates for atomic oxygen interactions with materials will be obtained by operating the mass spectrometer in the aeronomy mode (+Z-axis) and orienting the Orbiter such that specimens installed on heated trays and disk holders (Fig. 4) are subjected to direct oxygen impingement. Whereas mass spectrometer density measurements will be made while the flight is in progress, mass loss determinations for highly reactive materials will be obtained when the mission is completed. To obtain the required exposure conditions, it is being requested that the Orbiter be flown for 40 hr in a circular orbit (variable inclination) with its payload bay oriented into the velocity vector (+ZVV) at an altitude of 222 km (120 n. mi.). Computations indicate that this exposure should result in day-night number densities (Fig. 5) sufficiently high to produce atomic oxygen fluxes in the range 1.1×10^{15} to 1.5×10^{15} atoms/cm^2-sec. This flux, in turn, will produce an accumulated fluence of 1.8×10^{20} atoms/cm^2. Using interaction data derived from previous Space Shuttle flights, it is estimated this fluence will result in surface recessions of 3 to 5 μm for materials (organic films, polyimide paints, and composites) that are susceptible to atomic oxygen interactions. A typical mass spectrometer measurement sequence for obtaining accurate reaction rates is shown in Fig. 6.

Less reactive materials, such as fluoropolymers, will be evaluated during this mission using quartz crystal microbalances (QCM's) to measure low rates of surface recession. These instruments have been selected for this application since they have high sensitivity (1×10^{-9} g/cm^2) in comparison to postflight weight loss determinations.(8) Although this exposure is several orders of magnitude less than the fluence Space Station structures will encounter(9) over an 11-yr solar cycle (2.5×10^{21} to 1.2×10^{22} atoms/cm^2), it will be sufficiently high to obtain accurate interaction rates for the materials evaluated.

Additional Measurements

As currently designed, this flight experiment will include additional sensors to study in greater detail the effects of atomic oxygen interactions with surfaces. In addition to the mass spectrometer, the carousel, the QCM's, and the passive disk holders discussed earlier, the experiment will include stress fixtures (Fig. 7) to study the effects of mechanical stress on erosion rates, heated disks and filmstrips to study the effects of temperature on interaction rates, and scatterometers to estimate energy accommodation on surfaces and define surface-atom emission characteristics as related to surface recession. A solar ultraviolet experiment, similar to one flown on the STS-8 mission, will be used to assess the effects of solar radiation on reaction rates. This device will consist of control (uncovered) specimens and specimens that are alternately exposed during the

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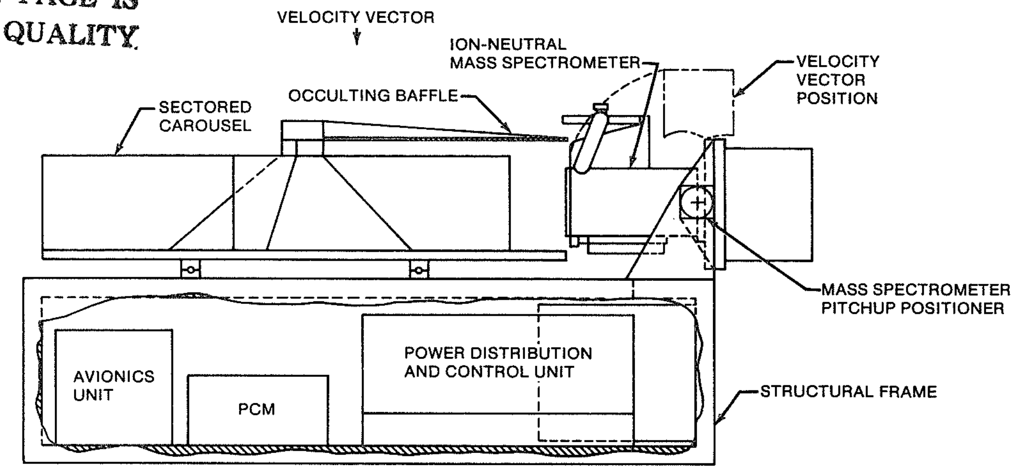
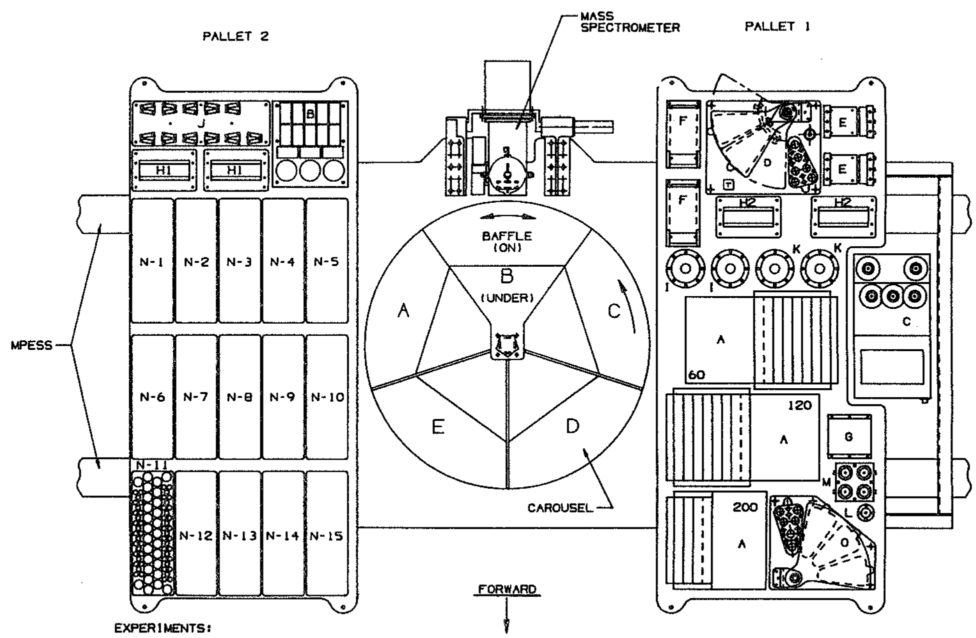


Fig. 3 Mass spectrometer/carousel flight configuration.



EXPERIMENTS:

A - HEATED PLATE (JSC), 3 EA
B - ATOM SCATTERING EXPERIMENT (UAH), 1 EA
C - ENVIRONMENT MONITOR PACKAGE (GSFC), 1 EA
D - SOLAR UV EXPERIMENT (JSC), 1 EA
E - STATIC STRESS FIXTURE (MSFC), 2 EA
F - UNIFORM STRESS FIXTURE (MSFC), 2 EA
G - ATOMIC OXYGEN MONITOR (MSFC), 1 EA
H1- COMPOSITE STRESS FIXTURE (LaRC), 2 EA
H2- COMPOSITE STRESS FIXTURE (JSC), 2 EA
I - SCATTEROMETER (JPL), 2 EA
J - MECHANICAL STRESS FIXTURE (LeRC), 11 EA
K - REFLECTOMETER (LeRC), 2 EA
L - PIN-HOLE CAMERA (LeRC), 1 EA
M - SCATTEROMETER (AEROSPACE CORP.), 1 EA
N - SAMPLE CARRIERS, 15 EA
O - VARIABLE EXPOSURE TRAY, 1 EA

Fig. 4 EOIM-3 atomic oxygen interaction experiment.

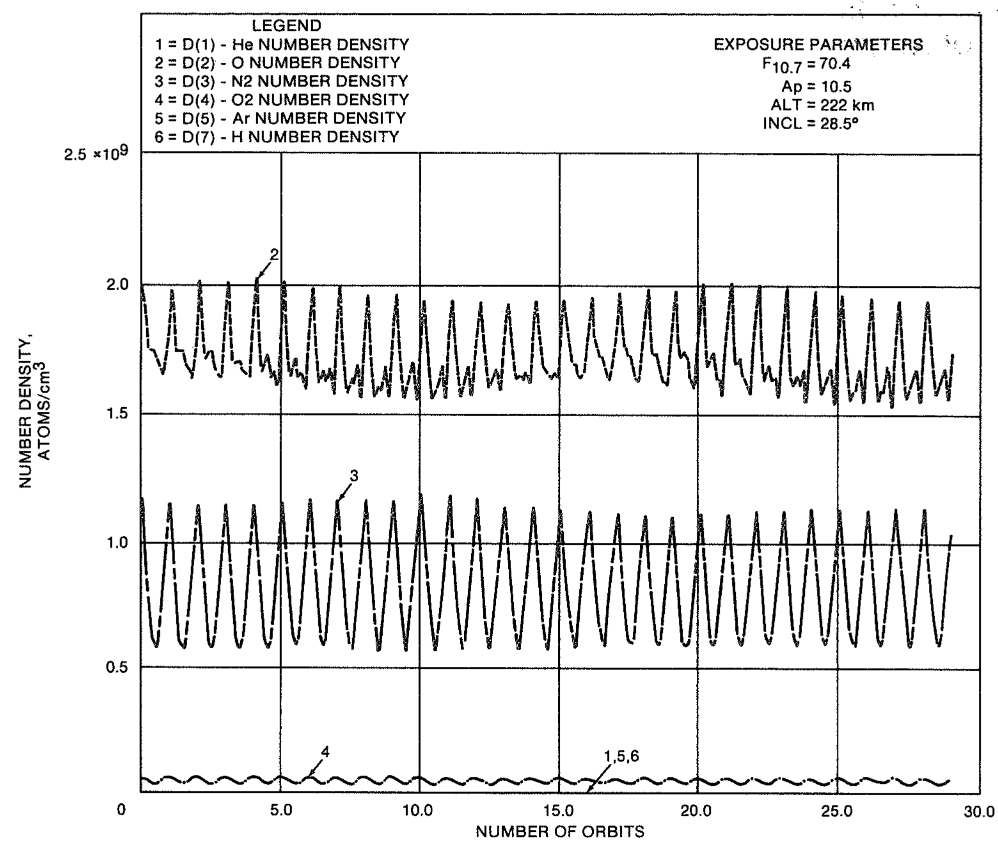


Fig. 5 Atmospheric density estimations for May 6, 1988, launch date.

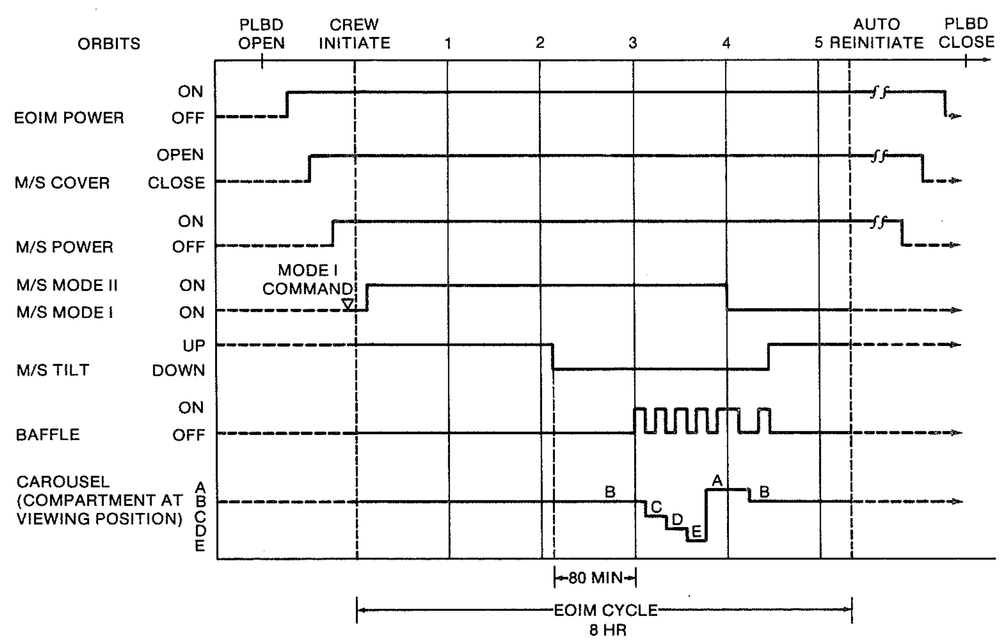


Fig. 6 EOIM-3 mass spectrometer measurement sequence, typical 8-hr exposure cycle.

day and night portions of the 40-hr exposure cycle. A similar device, the variable exposure experiment, will be used to assess the effects of matrix shadowing on reaction rates. Previous flight results have demonstrated nonreactive fillers lower the reactivity of polymers by shadowing the organic matrix. The variable exposure experiment will sequentially expose filled polymers at 5, 10, 20 and 40 hour intervals to evaluate how their surface recession varies with exposure time. Reaction rates will be derived for materials selected for each of these experiments by using the mass spectrometer to measure variations in day-night number densities, by determining the exposure time, and by performing postflight weight loss measurements.

The locations of these devices, as currently proposed for this flight experiment, are shown in Fig. 4. These locations, in addition to the location of the mass spectrometer/carousel system, have been chosen to minimize tray dimensions, to isolate products outgassed from the heated (60°, 120°, 200° C) trays from the mass spectrometer, and to limit uncontrolled scattering of the oxygen beam onto sensitive surfaces.

Experiment Status

Flight hardware is under development at the NASA Lyndon B. Johnson Space Center (JSC) and the U.S. Air Force Geophysics Laboratory. Passive and active experiments and material specimens will be provided by most NASA centers and by the Space Station work package contractors. Experiments under development by the NASA centers (JSC, Goddard Space Flight Center (GSFC), George C. Marshall Space Flight Center (MSFC), Langley Research Center (LaRC), Jet Propulsion Laboratory (JPL), and Lewis Research Center (LeRC)), by an aerospace contractor (Aerospace Corp.), and by the University of Alabama at Huntsville (UAH) are identified, by organization, in Fig. 4, which illustrates the locations of the mass spectrometer and carousel, and the configuration of the active and passive trays discussed earlier.

The experiment program plan and request for flight assignment have been approved by the NASA offices (Space Station and Office of Aeronautics and Space Technology) who will provide funding for hardware development. The flight readiness date for this experiment is tentatively scheduled for May 1988. A flight assignment date has not been established by NASA; however, it may occur as soon as early- to mid- 1988, since these investigations directly support Space Station advanced development.

Mass Spectrometer Preflight Calibrations

The mass spectrometer will be calibrated in an atomic oxygen neutral beam facility, under development at Los Alamos National Laboratory, to obtain accurate aeronomy measurements during the flight. Atomic oxygen is being produced at this facility[10] by sustaining a discharge with a high-intensity continuous-wave (CW) laser in a mixture of rare gas and molecular oxygen. The high-temperature discharge region dissociates the molecular oxygen into atoms, which are allowed to expand through a nozzle into a differentially pumped chamber. The facility in which the mass spectrometer will be calibrated will use a 1.5-kW CW laser to sustain a discharge within

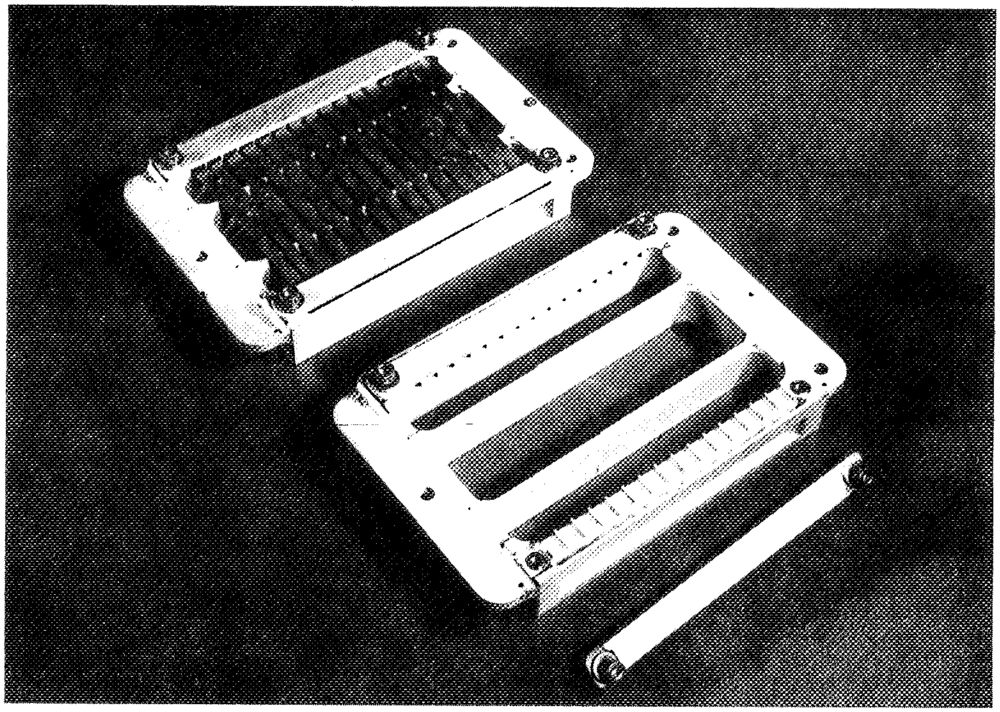


Fig. 7 Mechanical stress fixture for composite materials.

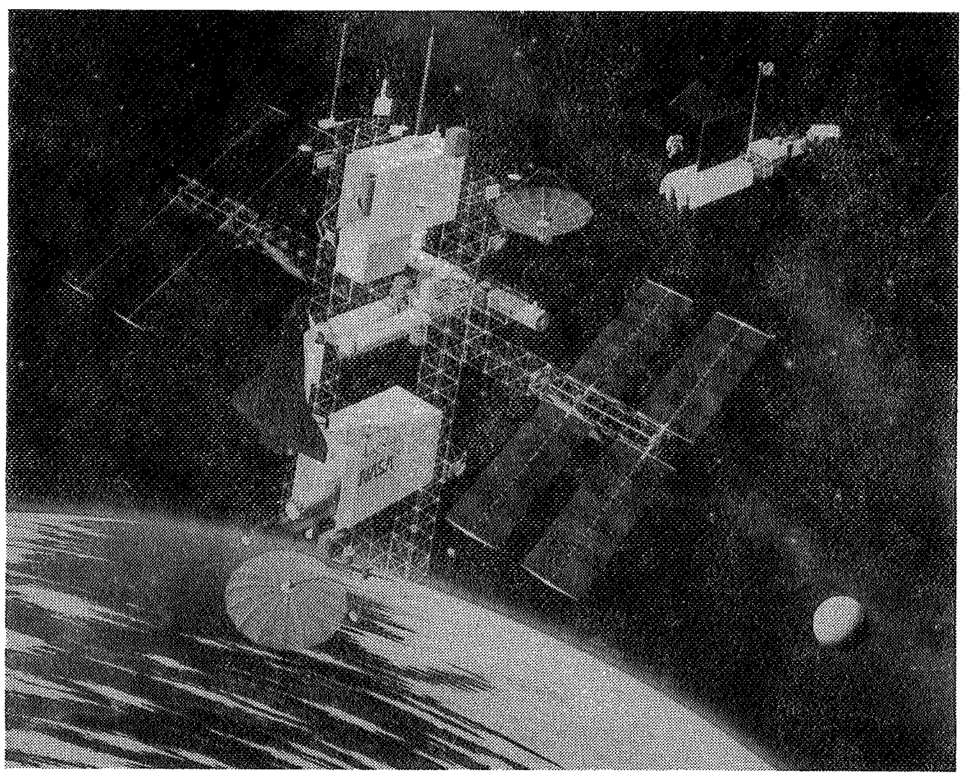


Fig. 8. Space Station dual-keel configuration.

a helium-oxygen mixture. It is anticipated that use of this mixture will produce oxygen atoms in the 5-eV range, as required for the flight simulation. The system will be designed to produce atomic oxygen fluxes of 10^{16} to 10^{17} atoms/cm^2-sec or less to accurately simulate the flight environment and later to provide capability for accelerated testing.

Interaction efficiencies and view factor calculations for carousel surfaces indicate that the amplitude of mass peaks recorded by the mass spectrometer during flight should be in the range 2×10^{-9} to 6×10^{-9} A, sufficiently above the expected instrument background current of 5×10^{-11} A recorded during previous missions.(11) To verify these calculations, materials such as polyimide and polyethylene will be exposed to the neutral oxygen beam, and the mass spectrometer will be oriented inside the target chamber to view products generated during the interaction process. The sensitivity of the instrument will be optimized to detect the interaction products. Final calibration will be performed by exposing the mass spectrometer to a 5-eV neutral oxygen beam to study recombination effects inside the ion source and to derive its measurement sensitivity for atomic oxygen.

Conclusions

The experiment described in this paper will provide a reliable materials interaction data base for future spacecraft design and will furnish insight into the basic chemical mechanisms leading to atomic oxygen interactions with surfaces. The effects of solar radiation and mechanical stress on erosion rates as well as scattering of atomic oxygen by various surfaces will enable derivation of protection techniques to ensure long-lived operation of lightweight Space Station structures and components. Such protective techniques as special coatings for truss structures and lightweight power generation devices, if properly applied, will be important considerations in designing a large, multipurpose Space Station, such as the NASA dual keel configuration shown in Fig. 8, that requires minimum refurbishment and limited component replacement over its lifetime.

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